# Precise Time Synchronization of Two Milstar Communications Satellites Without Ground Intervention

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Col. J. Sovey
SMC/MC

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Satellite navigation and communication systems often require precise synchronization among spacecraft clocks. In the traditional method for achieving synchronization, a ground station makes time-offset measurements to the various spacecraft clocks, and then updates the time and frequency of each satellite as needed. Though straightforward in its implementation, disadvantages to the traditional approach include the large workload placed on the ground station, the need for multiple ground stations to view satellites in different geosynchronous positions, and unaccounted-for delays in atmospheric propagation. In early 1996, Milstar became the first satellite system to employ crosslinks for precise satellite time synchronization. At that time, the crystal oscillator clock onboard FLT-1, the first Milstar satellite, had its time and frequency tied (i.e., slaved) to the rubidium (Rb) atomic clock carried onboard FLT-2, the second Milstar satellite. The FLT-2 Rb atomic clock was controlled by the ground, while the slaving of FLT-1 to FLT-2 was accomplished without ground intervention: all timing information required by the slaving algorithm was obtained through the FLT-1 to FLT-2 satellite crosslink. Timekeeping capabilities of the two satellite clocks when operating independently are shown, which indicate that both clocks are performing well. Then the ground station measurements of FLT-1 and FLT-2 timekeeping are presented that demonstrate satellite synchronization to better than 150 ns without ground intervention. As satellites are added to the Milstar constellation, crosslink slaving will minimize ground station timekeeping activities, thereby lowering system operating costs.

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## INTRODUCTION

Satellite navigation and communication often require fairly precise synchronization among spacecraft clocks. In the traditional method for achieving synchronization, a ground station makes time-offset measurements to the various spacecraft clocks, and then updates the time and frequency of each satellite as needed. Though straightforward in its implementation, disadvantages to the traditional approach include the large workload placed on the ground station, the need to have several ground stations to view satellites in different orbital locations, and unaccounted-for delays in atmospheric propagation.

The Milstar communications system has chosen a different method for spacecraft synchronization. Milstar's mission is to provide secure antijam communication capabilities for United States Department of Defense operations into the next century,[1] and in order to accomplish that task Milstar employs precise timekeeping on its satellites and at its ground control stations.[2] A Milstar ground station makes time-offset measurements to an in-view geosynchronous satellite, which for this illustrative discussion we will assume is the Master, and as a result of information passed along the satellite crosslinks, other satellites in the constellation (i.e., Slaves) autonomously synchronize themselves to the Master. Since the ground station only needs to steer the time and frequency of a single satellite, its workload, and hence the timekeeping-related operational costs of the system, are held to a minimum. Moreover, since synchronization among the satellites is accomplished without transmission through the ionosphere, atmospheric propagation delays cannot perturb the synchronization among spacecraft clocks.

The first of six Milstar satellites, FLT-1, was launched on 7 February 1994, while FLT-2, the second Milstar satellite, was launched on 6 November 1996. Each satellite carries a set of precise clocks: FLT-1 carries crystal oscillator clocks, while FLT-2 carries more accurate rubidium (Rb) atomic clocks.[3,4] The ground stations maintain precise time with cesium (Cs) atomic clocks.[4] Following the launch of the second Milstar satellite, crosslinks between FLT-2 and FLT-1 were activated and FLT-1's timekeeping was slaved to FLT-2. In the slaving procedure, FLT-1 uses satellite crosslink information to rapidly correct its time so as to stay synchronized to FLT-2, and to periodically correct its oscillator

frequency. FLT-2 is synchronized to true time (essentially Coordinated Universal Time which is abbreviated as UTC[4]) by a ground station that periodically collects timing information from the satellite, and after a number of days commands time and frequency adjustments to the FLT-2 satellite clock.[5] Timekeeping data can be collected by ground stations for both satellites, and is archived along with any commanded time and frequency corrections. Using the archived data we have been able to reconstruct 'raw' time-offsets for the FLT-1 and FLT-2 clocks, that is the time-offsets that would have been observed on the ground had the ground station made no time or frequency corrections to the satellite clocks. In the following we will show that an Allan variance analysis of these raw time-offsets indicates that each clock is performing well, and that when crosslink synchronization is initiated FLT-1 achieves a 150 nsec or better synchronization to FLT-2 without assistance from the ground.

## FLT-1 AND FLT-2 CLOCK PERFORMANCE

### Deterministic Timekeeping Variations

The reconstructed raw time-offset measurements of FLT-1 and FLT-2 are displayed by the thick lines in Figs. 1a and 1b respectively; thin lines show quadratic fits to the data. (In both figures, initial time and frequency offsets were subtracted from the data sets to better display the quadratic variation of time-offset; and of course, the *actual* timekeeping performance of the satellites was better than that shown in the figure due to periodic updates from the ground.) The quadratic fits model deterministic variations in the clocks' timekeeping,[4] and in particular the quadratic coefficients are measures of the clocks' fractional frequency drift rates (i.e., drift $= dy/dt$, where $y$ is the fractional frequency offset defined as $\delta f/f_0$ with $\delta f$ a frequency variation from the nominal frequency $f_0$). After a clock has been operating for some time, so that 'turn-on' transients have died away, these drift rates are expected to be either constant or to change very slowly with time. For FLT-1, the quadratic fit yields a drift rate of $+9.8 \times 10^{-13}$/day, which is quite good for a crystal oscillator clock.[6] Moreover, FLT-1 has exhibited this same drift rate since October 1994. (The variations of timekeeping about the quadratic fit are an indication of stochastic fluctuations in the
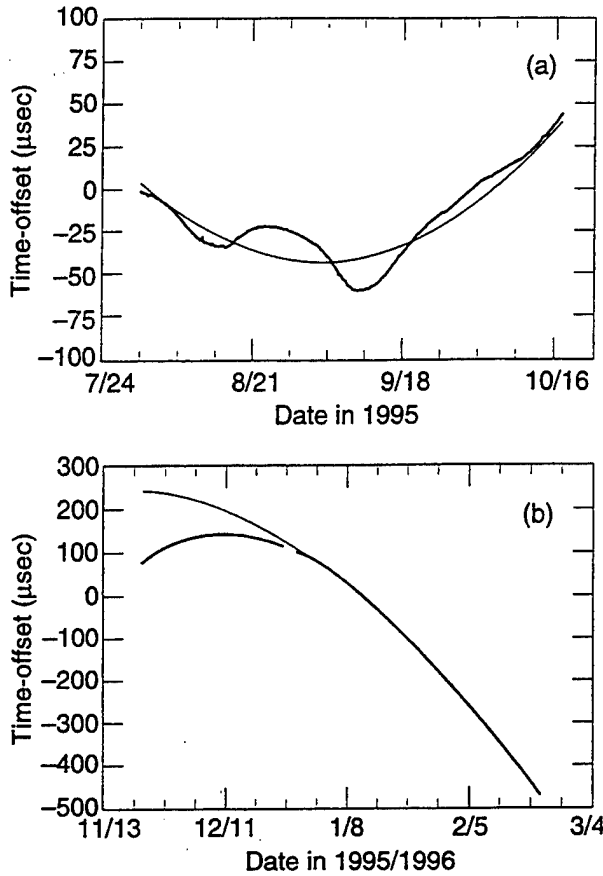
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Figure 1. (a) Raw time-offset history of the crystal oscillator clock onboard FLT-1 (thick line). (b) Raw time-offset history of the Rb atomic clock onboard FLT-2 (thick line). Thin lines correspond to least squares quadratic fits to the data, and minor divisions of the abscissa correspond to seven day intervals

## Allan variance

Taking the difference between the raw time-offset measurements and the quadratic fit, time-offset residuals may be computed. These residuals represent stochastic variations in the clock's timekeeping, and are typically assessed in terms of the Allan variance of fractional frequency fluctuations, $\sigma_y^2(\tau)$, where $\tau$ is the averaging time associated with a particular measurement of clock oscillator frequency:[8]

$$\bar{y}_i = \frac{1}{\tau} \int_{t_i}^{t_i+\tau} y(t)\, dt, \qquad (1a)$$

$$\sigma_y^2(\tau) = \frac{1}{2(m-1)} \sum_{i=1}^{m-1} (\bar{y}_{i+1} - \bar{y}_i)^2. \qquad (1b)$$

Here, m is the number of fractional frequency values for averaging time $\tau$. From a practical standpoint, computation of the Allan variance statistic requires uniformly spaced measurements of oscillator frequency. Since the archived ground station measurements, and hence the time-offset residuals, are not separated by a constant interval, interpolation of the data is necessary in order to generate a history of fractional frequency fluctuations amenable to Allan variance analysis. Vernotte et al.[9] have shown that a Linear-Interpolation (LI) procedure is a viable strategy for interpolating unevenly spaced time error data, and we have employed their approach here. With the LI procedure, the fractional frequency fluctuation of an oscillator at some time t (such that $t_k \le t < t_{k+1}$) is given by

$$y(t) = \frac{x(t_{k+1}) - x(t_k)}{(t_{k+1} - t_k)}, \qquad (2)$$

where $x(t_k)$ is the time-offset residual at time $t_k$.

Figure 2 shows the resulting Allan standard deviation, $\sigma_y(\tau)$, versus $\tau$ for the FLT-1 crystal oscillator clock and the FLT-2 Rb atomic clock. Dashed lines correspond to estimates of the Allan standard deviation based on a simple model: satellite to ground-station time-transfer noise dominates the Allan variance for $\tau \le 10^5$ seconds, while random-walk frequency noise dominates $\sigma_y(\tau)$ for longer averaging times. (Satellite to ground-station time-transfer noise is associated with randomly varying delays at the transmitter and receiver). For the crystal oscillator

clock's timekeeping as will be discussed subsequently.) Analysis of the data presented in Fig. 1b indicates that FLT-2 has a drift rate of $-1.5 \times 10^{-12}$/day. Though the magnitude of this drift rate is a bit larger than that of the crystal oscillator clock, it is nonetheless consistent with pre-launch expectations for the FLT-2 Rb atomic clock at this point in its operating life. With continued operation, the slowly varying frequency drift rate should drop well below the $10^{-12}$/day level and should eventually become constant. (The deviation of the raw time-offset data from the quadratic for the early part of FLT-2's time-offset history is a consequence of the atomic clock's warm-up behavior.[7]) The important point to note from Fig. 1 for future discussion is that the drift rate of the FLT-1 clock is distinctly different from that of the FLT-2 clock.
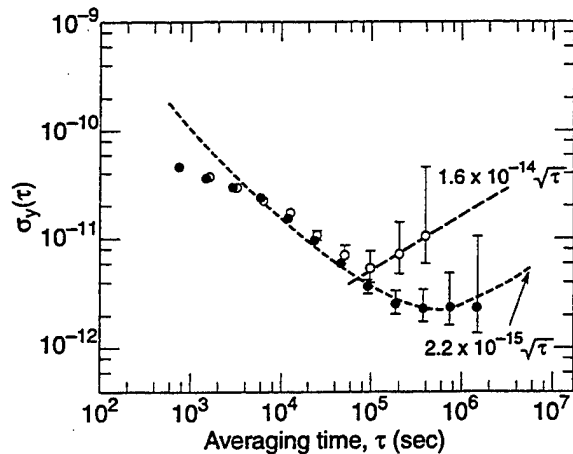
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Figure 2. Allan standard deviation, $\sigma_y(\tau)$, versus averaging time $\tau$ for the FLT-1 crystal oscillator clock (open circles) and the FLT-2 Rb atomic clock (filled circles). The short dashed curve is the anticipated Allan standard deviation for the Rb atomic clock, while the long dashed curve corresponds to the crystal oscillator clock's random-walk of frequency noise
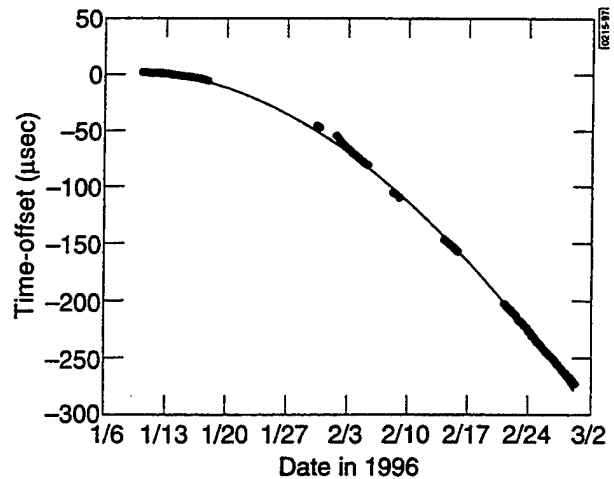


Figure 3. Raw time-offset of the FLT-1 crystal oscillator clock (black points) while it was slaved to the FLT-2 Rb atomic clock. The thin curve is a least squares quadratic fit to the data

clock the long-term Allan standard deviation is well modeled by $\sigma_y(\tau) = 1\cdot6 \times 10^{-14}\, \tau^{1/2}$, a value consistent with a high performance crystal oscillator clock.[10] For the Rb atomic clock the long-term Allan standard deviation is well modeled by $\sigma_y(\tau) = 2\cdot2 \times 10^{-15}\, \tau^{1/2}$, again a value consistent with a well-functioning device.[11] We note that the lower value of random-walk frequency noise for the Rb atomic clock, compared to the crystal oscillator clock, is the reason for its superior timekeeping capability.

## SATELLITE CLOCK AUTONOMOUS SYNCHRONIZATION

As noted in the Introduction, following the launch of FLT-2 the FLT-1 satellite became a slave to FLT-2, and therefore tied its crystal oscillator clock to the FLT-2 atomic clock using crosslink timing information. Given the archived data of FLT-1's time-offset during the slaving period, along with ground station corrections to FLT-2 and FLT-1, it is possible to reconstruct the timekeeping behavior of FLT-1 while it was slaved to FLT-2. This is shown in Fig. 3, where the black data points correspond to FLT-1 raw time-offset measurements, and the curve is a quadratic least squares fit to the data. (We note for future reference that FLT-1 slaving to FLT-2 was deactivated for several days during this

period). The fit yields a fractional frequency drift rate of $-2\cdot3 \times 10^{-12}$/day. This is to be compared with the FLT-1 crystal oscillator's intrinsic drift rate of $+9\cdot8 \times 10^{-13}$/day. The roughly $-3 \times 10^{-12}$/day change observed in FLT-1 crystal clock drift is not due to a problem with the clock, but rather to the fact that during this period the FLT-1 clock maintained tight synchronization to the FLT-2 Rb atomic clock, which had a negative drift rate. We further note that the discrepancy between the $-2\cdot3 \times 10^{-12}$/day drift rate of FLT-1 and the $-1\cdot5 \times 10^{-12}$/day drift rate of FLT-2 is a consequence of the few days during this period when slaving was turned off. If an attempt is made to account for those few days, the FLT-1 and FLT-2 drift rates become nearly identical.

An estimate of the level of synchronization between FLT-1 and FLT-2 may be obtained from raw time-offset measurements made to both satellites by a single ground-station. As illustrated in Fig. 4 this occurred in early February of 1996. On 8 February 1996 a ground-station commanded a time and frequency correction to the FLT-2 atomic clock, and then began making time-offset measurements to FLT-1 (filled circles in the figure). Then, on 9 February 1996 the same ground station began making time-offset measurements to FLT-2 (open circles in the figure). The solid line is a quadratic fit to all the data, clearly indicating that the ground-station
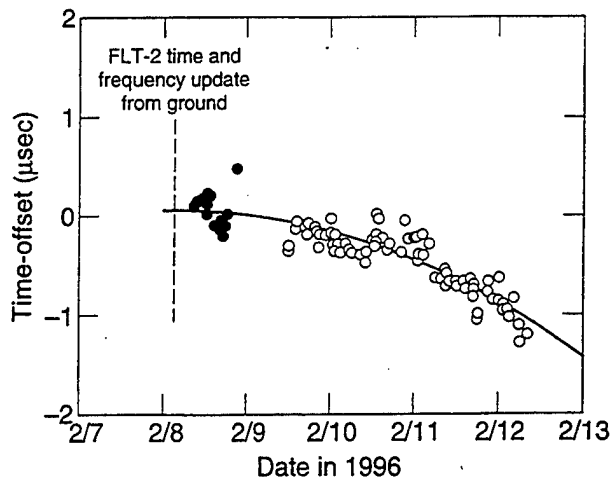
Figure 4. Raw time-offset measurements of the FLT-1 crystal oscillator clock (filled circles) and the FLT-2 Rb atomic clock (open circles) by the same ground-station. The solid line is a quadratic fit to all the data

synchronized FLT-2 to true time. FLT-1 was not corrected by any ground command, but rather by autonomous crosslink synchronization to FLT-2. Based on the deterministic and stochastic variations of the crystal clock's timekeeping, and the fact that FLT-1 received its last correction from the ground on 4 February, FLT-1's time offset from true time should have been appreciable on the scale of Fig. 4 (i.e., at the 1–$\sigma$ level somewhere within ~ $\pm 3$ $\mu$sec of true time). However, as a consequence of crosslink synchronization to FLT-2, FLT-1's time-offset from true time was near zero.

Computing the standard deviation of time-offset residuals from the quadratic regression line in Fig. 4, we have $\sigma_{FLT-2} = 141$ nsec and $\sigma_{FLT-1} = 207$ nsec. These variations about the regression line are a consequence of: 1) satellite to ground-station time-transfer noise, 2) diurnal oscillations due to the satellite clocks' temperature sensitivities, and 3) crystal oscillator and atomic clock noise processes. Additionally, the FLT-1 variations must include the residuals associated with the slaving process. It should be noted, though, that the clock noise contribution to $\sigma_{FLT-X}^2$ will be larger for FLT-1 than for FLT-2 due to the Rb clock's smaller value of random-walk frequency noise. Also, any temperature contribution to $\sigma_{FLT-X}^2$ will be larger for FLT-1 than for FLT-2 due to the Rb clock's inherently lower sensitivity to temperature variations. Consequently, if we assume that the various processes listed above contribute to $\sigma_{FLT-X}^2$ in an independent fashion, and

that the satellite to ground-station time-transfer noise contributes equally to $\sigma_{FLT-1}^2$ and $\sigma_{FLT-2}^2$, we can obtain an upper bound on the slaving process's error in synchronizing FLT-1 to FLT-2 by combining these two standard deviation values:

$$\sigma_{slaving} \cong \sqrt{\sigma_{FLT-1}^2 - \sigma_{FLT-2}^2} = 152 \text{ nsec.} \quad (3)$$

Thus, the data demonstrates that the two spacecraft were synchronized to within $\pm 150$ nsec, *independent of ground-station intervention.*

## CONCLUSIONS

As satellite navigation and communication applications increase, greater emphasis will be placed on synchronizing spacecraft clocks independent of ground intervention. In part, this situation will be motivated by a desire: 1) to reduce the workload at mission control ground stations and reduce system operating costs, 2) to control a geosynchronous constellation from a single location, and 3) to reduce unaccounted-for delays in atmospheric propagation. Milstar is the first satellite system to employ crosslink synchronization for geosynchronous spacecraft, and here we have demonstrated the efficacy of that method. Specifically, our results show that crosslink synchronization has allowed FLT-1 and FLT-2 to achieve a $\pm 150$ nsec (or better) level of synchronization without intervention from the ground.

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